Temperature of Shocked Materials

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Neutron resonance spectroscopy (NRS) uses the Doppler broadening of neutron resonances to determine the temperature in samples undergoing dynamic loading. This technique has emerged as a unique method for making temperature measurements in the field of shockwave and high-explosive physics—as such, it can be applied to Science-Based Stockpile Stewardship and the Weapons Program. NRS can determine temperatures on very short time scales (1 μs or less) and has been used to determine the internal volume temperature in shocked molybdenum and in explosively driven metal jets. In 2003, the NRS team began the first experiments to measure the temperature behind the burn front of detonating high explosives; measurements of this burn temperature have never before been made *in situ*. For many materials of interest, dynamic temperature measurements appear possible at many attainable conditions on the EOS surface.

Why Neutrons?

NRS experiments use low-energy neutrons because these minimally perturbing probes possess advantages over other available temperature diagnostics. First, optical opacity or ancillary light emissions do not limit the technique because photons are not detected. Second, the technique uses small amounts of resonant tags, or dopants, that can be localized in the samples being studied. For a given experiment, the type of dopant and quantity (about 1 at. %) is selected so that it causes minimal perturbations to the dynamically loaded sample. The localization of the doped region allows us to make temperature measurements in a steady shock region internal to the sample rather than at a free surface or visible interface where rarefactions can alter the state being characterized.

What is a Neutron Resonance?

When a beam of neutrons passes through a sample of atomic weight A, those neutrons possessing certain resonant energies (usually in the epithermal region below a few hundred eV) can be captured by sample nuclei to form an excited state in the "compound nucleus" of atomic weight A+1. The capture interaction removes neutrons from the beam passing through the sample. A detector placed downstream of the sample measures the neutron flux as a function of the time when the neutrons arrive; there are dips (Figure 1) in the observed spectra at the energies at which the compound nuclei were formed. The depths of the resonances and their energies are unique to the materials traversed by the neutrons. NRS experiments can take advantage of this uniqueness to localize temperature measurements in space by inserting a dopant that resides only in the region of interest. The shapes of these resonances depend on both intrinsic resonance properties and on the Doppler broadening produced by the motion of atoms in the target sample. By measuring the amount of broadening produced, NRS determines the temperature of the sample.

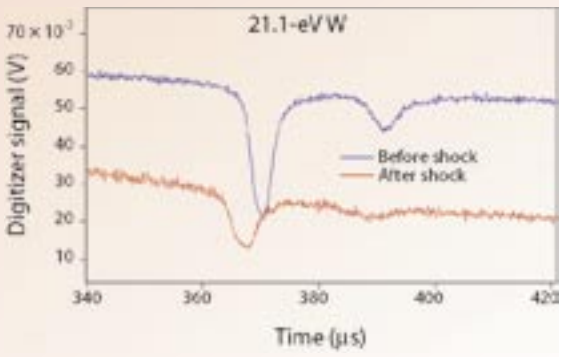


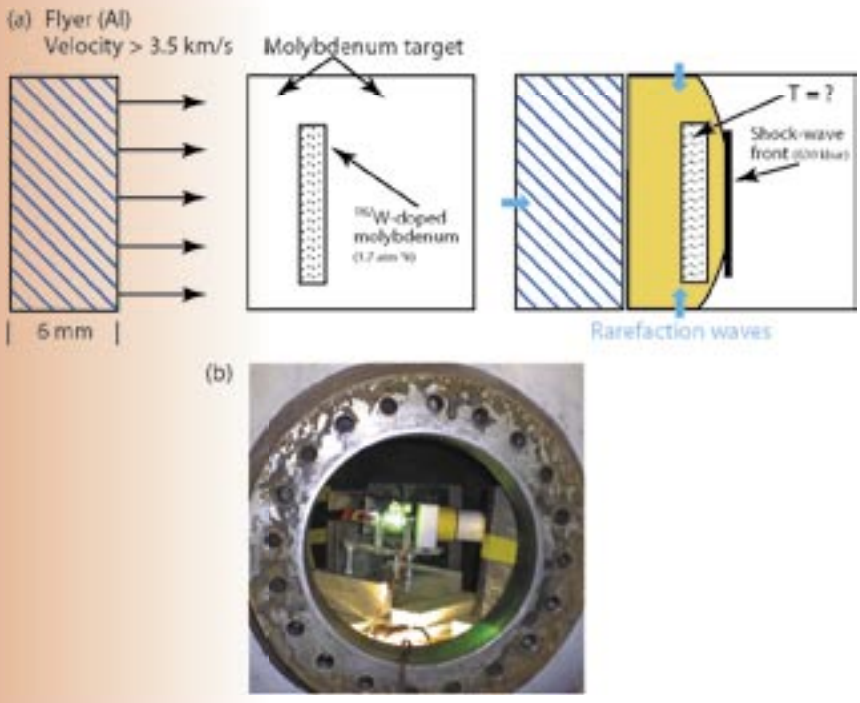
Figure 1. Resonances at 21 eV and 18 eV in the transmitted neutron flux through an isotopically enriched ^{182}W sample before and after the material is shocked. The two curves show the comparative broadening of the resonances, as well as the shifts in resonance positions.

LANSCE Accelerator Provides an Intense Source of Neutrons

Obtaining the necessary statistics for accurate NRS temperature measurements requires a copious source of epithermal neutrons in a single pulse. The linear accelerator at LANSCE produces 800-MeV protons that are loaded into the Proton Storage Ring where they are accumulated and then released as a short, intensified beam pulse. (Each pulse contains about 30 trillion protons.) The intense proton pulse is directed at a uranium spallation target and produces many high-energy neutrons upon striking the target. These high-energy neutrons then bounce around in a polyethylene moderator where they slow down to epithermal energies and emerge into the NRS secondary beam line. With this special setup, NRS achieves neutron brightness levels an order of magnitude higher than is presently available at the main LANSCE production target.

A fast temperature "snapshot" is required to study dynamically loaded systems. For instance, to measure the temperature after the passage of a shockwave, the measurement must be recorded after the sample is fully shocked but before any rarefactions return from the front, rear, or side surfaces. The time window for measuring the unreleased temperature in a shocked metal is about 1 μs (Figure 2). The time resolution of the NRS measurement is determined by the spread in transit times of resonant neutrons traversing the sample. In the Blue Room at LANSCE, the sample can be placed at a short distance (within 1 m) from the moderator, and fast time resolutions of several hundred nanoseconds are achievable.

Figure 2. Rendering of an NRS experiment to measure temperature in a shocked metal. (a) An explosively launched aluminum flyer initiates the shock in a molybdenum target, which contains a region doped with ^{182}W. Neutrons probe the doped region after the passage of the shock wave but before the return of rarefactions. Figure 2(b) is a view inside the target chamber used in the NRS experiment at LANSCE.



Temperature Behind the Passage of a Shock Wave in Molybdenum

The NRS experimental effort with highest priority is the measurement of the temperature behind a strong shock in a metal. This type of measurement provides a means for testing various EOS models. NRS is currently the only technique capable of measuring the internal temperature without significantly altering the shocked state. The NRS team has performed temperature measurements in molybdenum within 1 μs of the passage of a shock wave through the sample. Within the constraints imposed by the high-explosive load limit in the containment vessel, the sample size, geometry, and location of the doped region in the metal were selected to maximize the time between passage of the shock and the appearance of rarefaction waves at the doped region. A preliminary analysis of the NRS data indicates that two shots provided temperatures of 785 ± 59 K and 908 ± 35 K for particle velocities of 0.90 and 0.96 km/s, respectively. Figure 3 shows that both measured temperatures are higher than those presently predicted by the best SESAME EOS[1] for molybdenum (SESAME 2984).

For safety reasons, the dynamic shots are fired at an angle to the neutron beam so as to prevent penetration of the containment vessel windows by shrapnel. Because of this tilt angle, the beam does not arrive simultaneously at all parts of the doped layer. The nonsimultaneity of arrival can alter the perceived temperature; we are currently modeling the effect that the tilt of the sample has on the derived temperature. So far, the effect of the tilt is too small to account for the difference between our experimental results and theory. The NRS team is currently working on design changes for future experiments that would reduce the hydrodynamic effects introduced by the sample tilt. A review of the NRS program by the Campaign 2 management encouraged EOS studies in metals as a high priority. In the latter part of the LANSCE 2003–2004 run cycle, we plan to perform additional experiments on molybdenum and/or other metals.

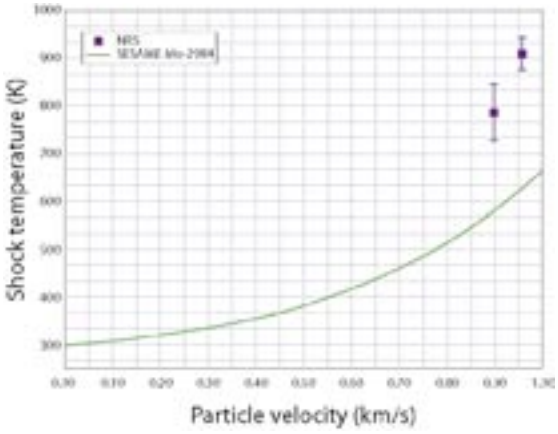


Figure 3. Shock temperature values extracted from NRS data are compared to theoretical values calculated using SESAME 2984 EOS. Temperatures are higher than the predicted values.

Measurement of the Temperature Behind the Burn Front of Detonating High Explosives

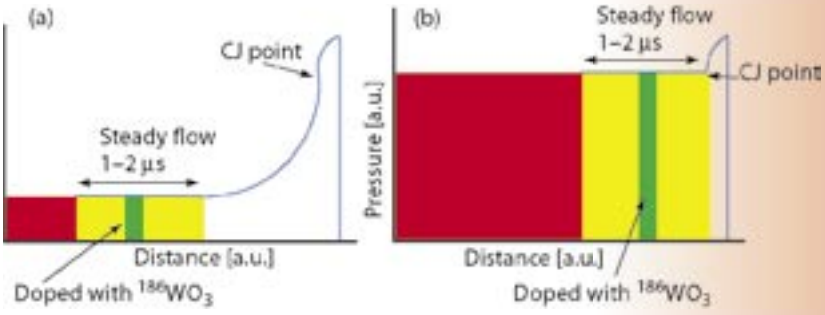
In a second experimental thrust, we measured the temperature behind the burn front of a high explosive detonated by a 6-mm-thick aluminum flyer plate. (The setup was similar to the one used in the shocked-metal experiment described above.) Through the use of a flyer plate, we can support the pressure behind the detonation front at a value just below the Chapman-Jouguet (CJ) point for the explosive (Figure 4). An NRS determination of the temperature inside detonation products of high explosives would fill a major gap in the characterization of its EOS. The largest uncertainty in theoretical modeling comes from the chemical equilibrium composition. Calculations by Sam Shaw (T-14) indicate that a shift from the combination of CO_2 and carbon in the products to CO can reduce the released energy by around 25%. Shaw calculates the corresponding shift in temperature to be around 1,000 K. This very strong correlation of the temperature with the composition is what makes the NRS measurements so useful. Several thermodynamic methods using potential energies exist for treating the EOS of high-explosive products, and these can be calibrated against experimental data. Additional calculations confirm that the WO_3 dopant has negligible effect on the high-explosive temperature. The fine-tuning of Shaw's model against NRS temperature measurements would greatly narrow the allowed parameter space and provide insight into the EOS of the high explosive.

The initial dynamic high-explosive EOS experiment performed by the NRS team did not result in a valid temperature measurement because of unanticipated dopant-clumping in the sample. Clumping can result in non-uniform thickness that distorts the extracted temperature; if the clumps are large enough, the temperature will not equilibrate within a clump. A subsequent NRS dynamic experiment used a new method of high-explosive formulation that was designed to reduce the clumping of the dopant in the high-explosive samples. Analysis indicates that the new formulation significantly reduced the clumping within the sample but did not completely eliminate it. The NRS measurement also indicated a particle velocity nearly one-half that predicted, but unfortunately the independent VISAR velocity measurement was lost because the VISAR optical fiber was damaged prematurely by the explosive. For future experiments, we will use a formulation of doped high explosive that incorporates nanoparticle tungsten-oxide dopant to further reduce non-uniformity and clumping. However, further shots may not take place until other higher-priority experiments are completed.

Measurement of the Temperature at a Sliding Interface at High Pressures and Velocities

Another challenge that the NRS team plans to address is determining the properties of a shocked metallic interface. One such interface of great interest exists between two materials possessing significantly different shock speeds. If a shock is initiated in both at the same time (Figure 5), the shock on one side of the interface will outrun the shock on the other side, causing the two materials to slide relative to each other at high velocity while experiencing a large normal force caused by the high-pressure shock. To date, there are no experimental data on the temperature rise at a compressed, sliding interface at high pressures and velocities. A constitutive model of the tangential

Figure 4. (a) This rendering depicts an unsupported detonation. (b) This rendering depicts how an aluminum flyer plate in the NRS experiment supports the pressure behind a detonation front at a value just below the CJ point for the explosive.



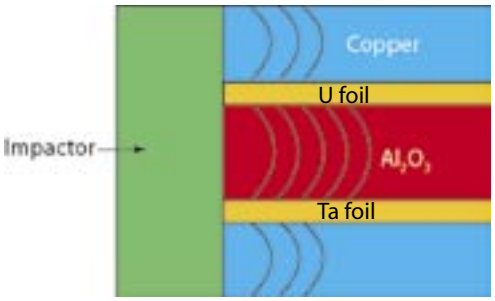


Figure 5. Schematic showing shock in sapphire (Al_2O_3) outrunning the shock in the adjoining copper. The neutron beam is passed through the sandwich, and resonances in Ta and U foils located at the Al_2O_3/Cu interfaces provide temperature data.

force as a function of pressure, temperature, sliding velocity, and the state of interfacial deformation at short times ($t < 50$ μs) was constructed.[2-4] However, there has been little in the way of experimental data to guide models that are important to the code development efforts of X Division. Measurements of the interfacial temperature will provide bounds on the parameters in the models and their uncertainties.

Our first NRS friction experiment will measure the temperature under dynamic conditions. The sample will consist of a sandwich comprised of an Al_2O_3 slab between slabs of copper (each slab being 2 cm thick). In addition, thin foils (50 to 100 μm thick) will be placed at the interfaces—a tantalum foil at one interface and a uranium foil at the other. An explosively launched aluminum flyer plate traveling parallel to the interfacial planes will impact the sandwich at about 2.5 km/s. Because shock in the Al_2O_3 travels much faster than the shock in the copper, a steady sliding state of about 1 cm in length should be achieved for a little over 1 μs. The shock pressure should be about 200 kbar, and relative interfacial velocities between the Al_2O_3 and foils should be about 0.5 km/s. The neutron beam will pass through the target while the temperature is elevated from the frictional heating. The temperature rise in the foils should be between 100 and 1,000 K, depending on the magnitude of the frictional force; by measuring the temperature, we should gain knowledge of the frictional force. There are resonance lines in tantalum and uranium at 39 eV and 37 eV, respectively, and they are separated enough in energy for temperature measurements to be possible at the two interfaces in the same experiment.

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